

Spin dependence of the $\bar{p}d$ and $\bar{p}^3\text{He}$ interactions

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Abstract. Elastic scattering of antiprotons on deuteron and ^3He targets is studied within the Glauber-Sitenko theory. In case of $\bar{p}d$ scattering, the single- and double $\bar{p}N$ scattering mechanisms and the full spin dependence of the elementary $\bar{p}N$ scattering amplitudes are taken into account on the basis of an appropriately modified formalism developed for pd scattering. Differential cross sections and analyzing powers are calculated for antiproton beam energies between 50 and 300 MeV, using the $\bar{N}N$ model of the Jülich group as input. Results for total polarized cross sections are obtained via the optical theorem. The efficiency of the polarization buildup for antiprotons in a storage ring is discussed.

1 Introduction

Scattering of antiprotons off polarized nuclei can be used to produce a beam of polarized antiprotons. Indeed, the PAX collaboration [1] intends to utilize elastic scattering of antiprotons off a polarized ^1H target in rings [2] as the basic source for antiproton polarization buildup. Analogous experiments performed for the proton case by the FILTEX collaboration [3] at 23 MeV and a recent COSY study where protons were scattering off a polarized hydrogen at 49 MeV [4] showed that a polarized beam can be achieved via this so-called spin-filtering effect. Whereas the spin dependence of the nucleon-nucleon (NN) interaction is very well known at the considered energies, that allows one to calculate reliably [5] the spin-filtering effect for protons, there is practically no corresponding information for the antinucleon-nucleon ($\bar{N}N$) interaction. For this reason a test experiment for the spin-filtering effect in the antiproton-hydrogen interaction is planned at the AD ring at the CERN facility [6, 7].

In view of the unknown spin dependence of the $\bar{p}N$ interaction, the interaction of antiprotons with a polarized deuteron is also of interest for the issue of the antiproton polarization buildup. This option was discussed in our paper [8] within the single-scattering approximation. The spin dependence of the elementary $\bar{p}N$ amplitudes was taken into account only in collinear kinematics using the $\bar{N}N$ interaction model of the Jülich group [9, 10, 11, 12] and total spin-dependent cross sections were calculated for energies in the region 50–300 MeV using the generalized optical theorem. A very similar analysis was performed by us for $\bar{p}^3\text{He}$ elastic scattering and the corresponding total cross sections were calculated [13]. However, spin observables for elastic

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scattering of antiprotons on light nuclei and shadowing effects (double scattering) in polarized total cross sections were not considered in those works. Spin observables are interesting quantities because they could be used for discrimination between existing models of the $\bar{N}N$ interaction once pertinent data become available [6, 7]. A calculation of such observables for the reaction $\bar{p}d \rightarrow \bar{p}d$, including double-scattering effects, was performed recently by us [14] and those results are reviewed here.

2 Method

Our study is based on the formalism derived by Platonova and Kukulin [15] within the Glauber-Sitenko theory of multistep scattering [16] and applied to pd elastic scattering – appropriately modified by us for the $\bar{p}d \rightarrow \bar{p}d$ transition. The single (SS) and double scattering (DS) mechanisms are included and the S - and D -components of the deuteron wave function and the full spin structure of the elastic $\bar{p}N$ scattering amplitude are taken into account. We refer the reader to Ref. [14] for details of the formalism. Here we only provide the expression of the $\bar{p}N$ scattering matrix which we need for the discussion lateron. It is given by

$$M_{\bar{p}N} = A_N + (C_N \boldsymbol{\sigma}_1 + C'_N \boldsymbol{\sigma}_2) \cdot \hat{\mathbf{n}} + B_N (\boldsymbol{\sigma}_1 \cdot \hat{\mathbf{k}}) (\boldsymbol{\sigma}_2 \cdot \hat{\mathbf{k}}) \\ + (G_N - H_N) (\boldsymbol{\sigma}_1 \cdot \hat{\mathbf{n}}) (\boldsymbol{\sigma}_2 \cdot \hat{\mathbf{n}}) + (G_N + H_N) (\boldsymbol{\sigma}_1 \cdot \hat{\mathbf{q}}) (\boldsymbol{\sigma}_2 \cdot \hat{\mathbf{q}}). \quad (1)$$

In Eq. (1), $\boldsymbol{\sigma}_1$ ($\boldsymbol{\sigma}_2$) is the Pauli matrix acting on the spin of the $\bar{p}N$ states ($N = p, n$). The unit vectors are defined by $\hat{\mathbf{k}} = (\mathbf{k}_i + \mathbf{k}_f)/|\mathbf{k}_i + \mathbf{k}_f|$, $\hat{\mathbf{q}} = (\mathbf{k}_i - \mathbf{k}_f)/|\mathbf{k}_i - \mathbf{k}_f|$, and $\hat{\mathbf{n}} = [\hat{\mathbf{k}} \times \hat{\mathbf{q}}]$, where \mathbf{k}_i (\mathbf{k}_f) denotes the momentum of the incident (outgoing) antiproton. The charge-exchange amplitude $M_{\bar{p}p \leftrightarrow \bar{n}n}$ has the same spin structure as given in Eq. (1).

The total $\bar{p}d$ and $\bar{p}^3\text{He}$ cross sections are defined by [8]

$$\sigma_{tot} = \sigma_0 + \sigma_1 \mathbf{P}_{\bar{p}} \cdot \mathbf{P}_T + \sigma_2 (\mathbf{P}_{\bar{p}} \cdot \hat{\mathbf{k}}) (\mathbf{P}_T \cdot \hat{\mathbf{k}}) + \sigma_3 P_{zz}, \quad (2)$$

where $\mathbf{P}_{\bar{p}}$ (\mathbf{P}_T) is the polarization vector of the antiproton (target), and P_{zz} is the tensor polarization of the deuteron target ($OZ \parallel \hat{\mathbf{k}}$) (for the ^3He target this term is absent). The total cross sections σ_i ($i = 0, 1, 2, 3$) are calculated using the generalized optical theorem as described in Refs. [8, 13].

3 Results and discussion

In Ref. [15] the Glauber-Sitenko formalism was successfully applied for describing spin observables of pd scattering at 250–1000 MeV, taking into account the full spin structure of the pN scattering amplitudes and the S - and D -components of the deuteron wave function. In order to test our own implementation of the formalism, we first tried to reproduce the numerical results of Ref. [15]. As example we present here pd results at 135 MeV, cf. Fig. 1, where one can see that this approach allows to explain reasonably well the differential cross section, the vector analyzing powers, and to some extent also the tensor analyzing power A_{xx} at this energy [17].

In the next step we use the modified formalism to calculate observables for $\bar{p}d$ elastic scattering. Earlier studies of the antiproton elastic scattering [18] and also our own previous calculations [8, 13] were all done within the spinless approximation for the elementary $\bar{p}N$ amplitude $M_{\bar{p}N}$, i.e. keeping only A_N from Eq. (1), and restricted to using only the S -wave part of the wave function of the target nucleus. In the present

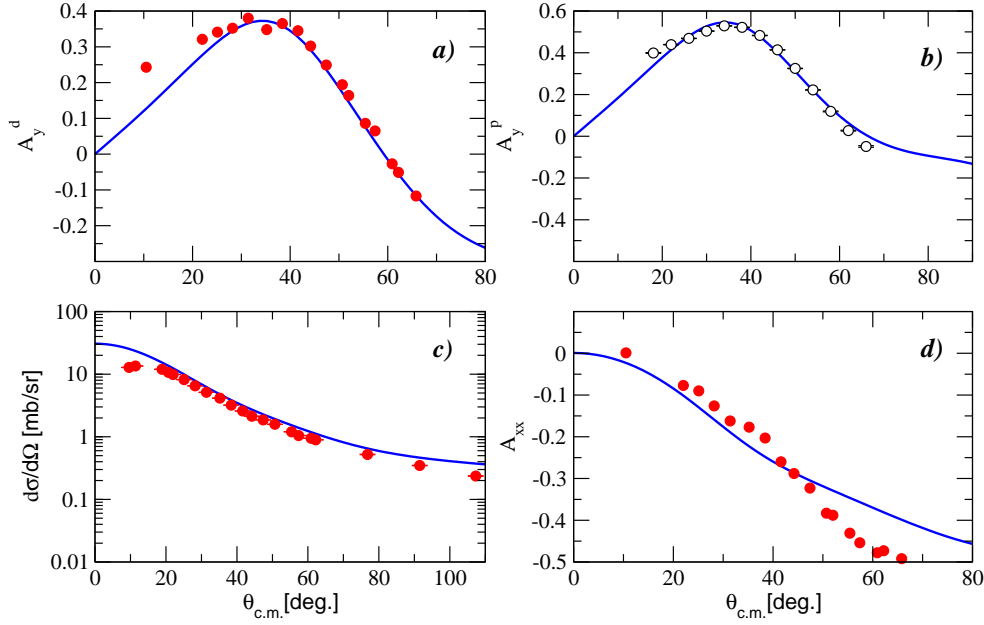


Fig. 1. Analyzing powers A_y^d (a), A_y^p (b), A_{xx} (d) and differential cross section (c) of elastic pd scattering at 135 MeV versus the c.m. scattering angle. Results of our calculations based on the Glauber-Sitenko approach are compared with data from Refs. [19] (filled circles) and [20] (open circles). The signs of A_y^p and A_y^d have been reversed in view of a different choice of the OY axis in Refs. [19,20] as compared to Ref. [15] (see the definition of \hat{n} after Eq. (1)).

calculation we keep the full spin dependence of the $\bar{p}N$ amplitude (see Eq. (1)) and employ two models developed by the Jülich group, namely A(BOX) introduced in Ref. [9] and D described in Refs. [11,12]. An exemplary result demonstrating the role of the single-scattering (SS) and double-scattering (DS) mechanisms is shown in Fig. 2a). One can see that the SS mechanism alone fails to explain the forward peak. However, the coherent sum SS+DS describes it rather well. Obviously, the DS mechanism, neglected in Ref. [8] in the calculation of the spin-dependent total cross sections, has a sizable influence even in the region of the forward peak.

Considering the spin-dependent terms of the $\bar{p}N$ amplitude, see Eq. (1), one has to address the following issue: In contrast to the spin-independent part A_N ($N = p, n$), most of the other terms that give rise to the spin dependence (B_N , C_N , C'_N , G_N , H_N) do not exhibit a well-pronounced diffractive behaviour for antiproton beam energies 50–200 MeV, i.e. they do not decrease rapidly with increasing center-of-mass (c.m.) scattering angle $\theta_{c.m.}$. As a consequence, the differential $\bar{p}N$ cross section has a minimum at scattering angle $\sim 100^\circ$ and a backward maximum [14]. One should note, that the Glauber-Sitenko approach is not suitable for taking into account backward scattering in the elementary hadron-nucleon collision, because its basis is the eikonal approximation. Therefore, any sensitivity of the observables calculated within this approach to the backward tail of the elementary $\bar{p}N$ amplitude is in contradiction with the assumptions of the Glauber-Sitenko theory and tells us that the corresponding calculations are no longer reliable. In the course of our investigation we studied this issue in detail by varying the employed elementary $\bar{p}N$ amplitudes in the backward-angle region and by examining the induced variations in the predictions for elastic $\bar{p}d$ scattering, see Ref. [14].

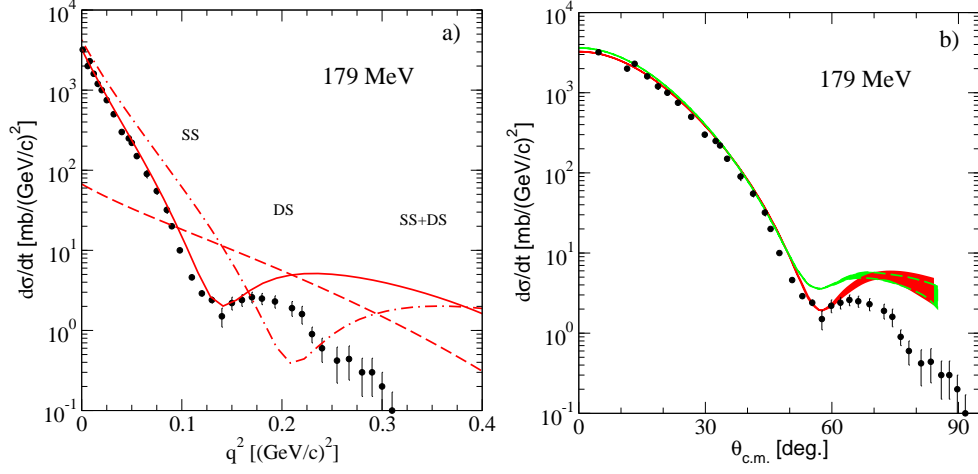


Fig. 2. Differential cross section of elastic $\bar{p}d$ scattering at 179 MeV. (a): results based on single-scattering (dash-dotted line), double-scattering (dashed) and the full (solid) Glauber-Sitenko mechanisms are shown for the model D. (b): Results of the full calculation are shown based on the $\bar{N}N$ models model A (green/grey) and D (red/black). The bands represent the sensitivity to variations of the large-angle tail of the $\bar{p}N$ amplitudes as discussed in the text. Data are taken from Ref. [21].

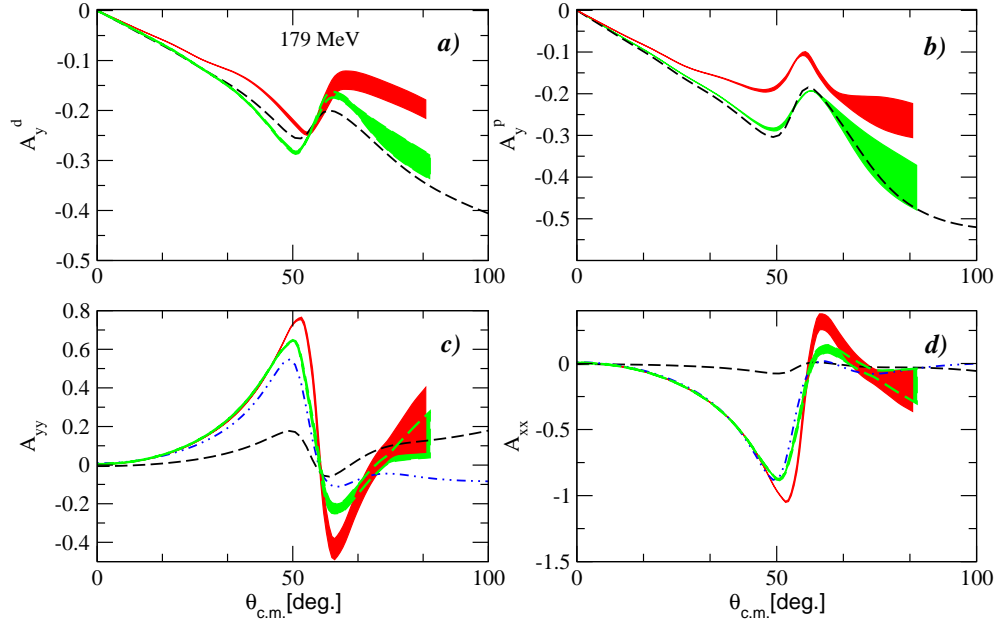


Fig. 3. Spin observables of elastic $\bar{p}d$ scattering at 179 MeV versus the c.m. scattering angle: A_y^d (a), A_y^p (b), A_{yy} (c), and A_{xx} (d). Results of our full calculation (including the SS+DS mechanisms) are shown based on the $\bar{N}N$ models model A (green/grey) and D (red/black). The bands represent the sensitivity to variations of the large-angle tail of the $\bar{p}N$ amplitudes as discussed in the text. The dashed line shows the result when the deuteron D -wave is omitted, based on model A, while the dash-dotted line in (c) and (d) corresponds to exclusion of the spin-dependent terms in Eq. (1).

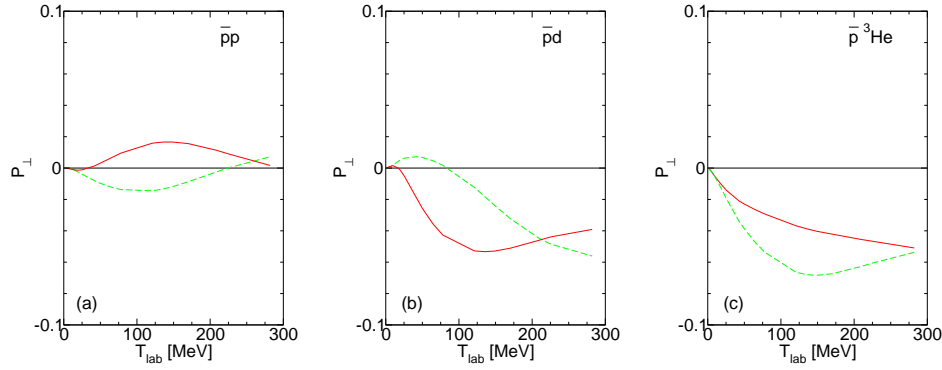


Fig. 4. Dependence of the transversal polarization P_{\perp} (i.e. $P_{\bar{p}}(t_0)$ for $\zeta \cdot \hat{\mathbf{k}} = 0$) on the beam energy for the target polarization $P_T = 1$ in the reactions $\bar{p}p$, $\bar{p}d$, and $\bar{p}^3\text{He}$. The results are for the models A (dashed line) and D (solid line). The employed acceptance angle is $\theta_{acc} = 10$ mrad.

The result of our analysis is summarized in Figs. 2–3. The bands represent the sensitivity of the calculated $\bar{p}d$ observables to variations of the backward tail of the elementary $\bar{p}N$ amplitudes. Thus, the widths of these bands is a sensible measure for estimating the angular region where the Glauber-Sitenko theory is able to provide solid results for a specific $\bar{p}d$ observable (vanishing width) and where it starts to fail (sizeable width). Our results suggest that for energies 50–300 MeV reliable predictions can be obtained within the Glauber-Sitenko approach for the differential cross section (Fig. 2) and also for the spin observables A_y^d , $A_y^{\bar{p}}$, A_{xx} , and A_{yy} (Fig. 3) for $\theta_{c.m.}$ up to $50^\circ - 60^\circ$ in the $\bar{p}d$ system. Obviously, within this angular region there is practically no sensitivity to the $\bar{p}N$ amplitudes in the backward hemisphere, in accordance with the requirements of the Glauber-Sitenko approach. As expected, due to the influence of the deuteron elastic form factor the width of the corresponding bands are smaller for higher energies and larger at lower energies, see the corresponding results in Ref. [14]. According to our calculations this (reliability) region includes the whole diffractive peak in the differential cross section at forward angles, for energies from around 50 MeV upwards. This finding validates the application of the optical theorem for evaluating the total polarized cross sections based on the obtained forward $\bar{p}d$ amplitude [8].

With regard to the measured differential cross section at 179 MeV, see Fig. 2b, our Glauber-Sitenko calculation describes the first diffractive peak quite well - for $\bar{p}N$ amplitudes generated from model A as well as for those of model D. The first minimum in the differential cross section, located at $q^2 \approx 0.12 - 0.13$ (GeV/c) 2 (i.e. $\theta_{c.m.} \approx 55^\circ$), and the onset of the second maximum is explained only by model D. The obvious strong disagreement with the data at larger transferred momenta, $q^2 > 0.15$ (GeV/c) 2 , corresponding to $\theta_{c.m.} > 60^\circ$, lies already in the region where the Glauber-Sitenko theory cannot be applicable anymore and, therefore, no conclusions can be drawn. In this context let us mention that the results shown in Fig. 2a were obtained with the full (unmodified) $\bar{p}N$ amplitudes as predicted by the Jülich $\bar{N}N$ model D.

The results obtained for the vector analyzing powers $A_y^{\bar{p}}$ and A_y^d indicate a strong model dependence (Fig. 3). When the spin-dependent terms of the elementary $\bar{p}N$ amplitude (B_N , C_N , C'_N , G_N , H_N) are excluded, then the vector analyzing powers $A_y^{\bar{p}}$ and A_y^d vanish. In contrast, the tensor analyzing powers A_{xx} and A_{yy} are much less sensitive to the $\bar{N}N$ models in question. Indeed, these observables are dominated

by the spin-independent amplitudes, see the dash-double dotted line in Fig. 3c and d. Thus, the results obtained here for A_{xx} and A_{yy} seem to be quite robust up to scattering angles of $60^\circ - 70^\circ$. The tensor analyzing powers A_{xx} and A_{yy} are reduced by one order of magnitude when the D -wave is omitted (dashed line in Fig. 3). Actually, A_{xx} and A_{yy} practically vanish if, in addition, the spin-dependent terms of the elementary $\bar{p}N$ amplitude are omitted.

To estimate the efficiency of the polarization buildup mechanism it is instructive to calculate the polarization degree $P_{\bar{p}}$ at the beam life time t_0 [22]. With our definition of σ_1 and σ_2 in Eq. (2) this quantity is given by

$$P_{\bar{p}}(t_0) = -2P_T \frac{\sigma_1}{\sigma_0}, \text{ if } \boldsymbol{\zeta} \cdot \hat{\mathbf{k}} = 0, \quad P_{\bar{p}}(t_0) = -2P_T \frac{\sigma_1 + \sigma_2}{\sigma_0}, \text{ if } |\boldsymbol{\zeta} \cdot \hat{\mathbf{k}}| = 1, \quad (3)$$

where the unit vector $\boldsymbol{\zeta}$ is directed along the target polarization vector P_T . Results for the transversal polarization P_{\perp} ($\boldsymbol{\zeta} \cdot \hat{\mathbf{k}} = 0$) are shown in Fig. 4. Since the $\bar{p}^3\text{He}$ cross sections were calculated in the single-scattering approximation [13], the results for $\bar{p}d$ interaction in Fig. 4 are likewise presented in this approximation. One can see that the polarization efficiency is comparable in absolute value for the reactions $\bar{p}p$, $\bar{p}d$, and $\bar{p}^3\text{He}$ [23]. However, since the total cross section is larger in case of ^3He the resulting efficiency of the polarization buildup tends to be somewhat smaller than those for $\bar{p}p$ and $\bar{p}d$.

The double scattering mechanism (shadowing effects), considered for $\bar{p}d$ in [14], decreases the absolute value of the polarized as well as of the unpolarized total cross sections and the polarization efficiency decreases too. Similar effects for $\bar{p}d$ were reported in Ref. [24] using amplitudes from the Nijmegen $\bar{p}p$ partial wave analysis [25].

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